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Research report

An enhanced role for right hV5/MT+ in the analysis of motion in the contra- and ipsi-lateral visual hemi-fields

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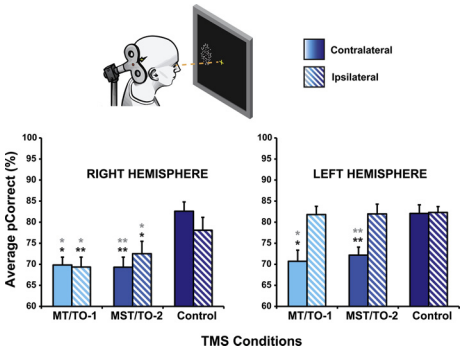
GRAPHICAL ABSTRACT



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ABSTRACT

Previous experiments have demonstrated that transcranial magnetic stimulation (TMS) of human V5/MT+, in either the left or right cerebral hemisphere, can induce deficits in visual motion perception in their respective contra- and ipsi-lateral visual hemi-fields. However, motion deficits in the ipsi-lateral hemi-field are greater when TMS is applied to V5/MT + in the right hemisphere relative to the left hemisphere. One possible explanation for this asymmetry might lie in differential stimulation of sub-divisions within V5/MT + across the two hemispheres. V5/MT + has two major sub-divisions; MT/TO-1 and MST/TO-2, the latter area contains neurons with large receptive fields (RFs) that extend up to 15° further into the ipsi-lateral hemi-field than the former. We wanted to examine whether applying TMS to MT/TO-1 and MST/TO-2 separately could explain the previously reported functional asymmetries for ipsi-lateral motion processing in V5/MT + across right and left cerebral hemispheres. MT/TO-1 and MST/TO-2 were identified in seven subjects using fMRI localisers. In psychophysical experiments subjects identified the translational direction (up/down) of coherently moving dots presented in either the left or right visual field whilst repetitive TMS (25 Hz; 70%) was applied synchronously with stimulus presentation. Application of TMS to MT/TO-1 and MST/TO-2 in the right hemisphere affected translational direction discrimination in both contra-lateral and ipsi-lateral visual fields. In contrast, deficits of motion perception following application of TMS to MT/TO-1 and MST/TO-2 in the left hemisphere were

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restricted to the contra-lateral visual field. This result suggests an enhanced role for the right hemisphere in processing translational motion across the full visual field.

1. Introduction

Asymmetries between the functional capabilities of the right and left cerebral hemispheres in the human brain have been reported for various aspects of sensory, motor and cognitive function such as language [1], attention [2], spatial processing [3], and face perception [4,5]. It is unclear whether functional lateralisation is also a feature that underpins the analysis of moving objects in the visual environment. Despite the fact that early visual areas have an almost exclusive representation of their respective contralateral visual fields, the perception of motion across the contra- and ipsi-lateral visual hemi-fields appears to be perfectly integrated for stimuli that span the vertical midline. A right hemisphere dominance has been shown to exist for the perception of motion trajectories [6] but, in general, brain imaging studies tend to reveal largely symmetrical bilateral activation across the cerebral hemispheres in response to moving visual stimuli [7–9].

Visual motion processing in the human brain is achieved as a result of neural activity which takes place across a distributed network of cortical areas, each of which is responsible for processing subtly distinct attributes of a moving visual scene [10,11]. A key area in this network is human (h)V5/MT+, which neuro-imaging studies [7–9,12,13] and neuropsychological studies of patients with brain damage that results in motion perception deficits [14–18], have identified as being located in the lateral occipito-temporal cortex. Importantly, a number of studies have also highlighted a potential role for hV5/MT + in the inter-hemispheric integration of motion processing across the contra- and ipsi-lateral visual hemi-fields [19–21]. However, there is a growing appreciation that this cortical region, rather than forming a single visual area, instead constitutes a complex comprising multiple visual areas, with each area making different contributions to our conscious perception of visual motion [22–25]. In this respect, the functional organisation of V5/MT + in the human brain mirrors that found in the non-human primate brain where V5/MT similarly comprises multiple visual areas, with each sub-division exhibiting distinct functional properties. For example, the posterior middle temporal sub-division (MT) appears to respond preferentially to 2D planar motion [26,27], whilst the more anterior dorsal middle superior temporal sub-division (MSTd) responds preferentially to visual features pertaining to optic flow e.g. radial, rotational, and spiral directional motion [28–30].

Following similar organisational principles, at least two, but possibly more (see: [25]), sub-divisions of hV5/MT + have also been identified in the human brain: MT/TO-1 and MST/TO-2 [22–24]. Neuro-imaging and neuro-stimulation evidence has shown that the more posteriorly located region, MT/TO-1, appears to be selectively responsive to local 'low-level' translational motion signals, whereas the more anterior MST/TO-2 sub-division appears to process both local and global motion signals, particularly those associated with optic flow [31–33]. Crucially, MT/TO-1 and MST/TO-2 also exhibit differences in the receptive field (RF) sizes of their constituent neuronal populations [24]. Within lower visual areas such as V1 and V2, the RF coverage of the constituent population of neurons typically falls within the contralateral visual hemi-field. However, within 'higher' visual areas neurons typically possess larger RF sizes which can extend across the vertical meridian, giving rise to partial coverage of the ipsi-lateral visual field [9,24]. In non-human primates there is evidence to suggest the RFs of neurons within motion area MST can extend up to 40 degrees into the ipsi-lateral visual field [34]. In humans, this encroachment of RFs into the ipsi-lateral field is evident to a certain extent within MST/TO-2, but exists to a much lesser degree in MT/TO-1 [24]. This differential representation of the ipsi-lateral visual field between MT/TO-1 and MST/TO-2 has formed the basis for reliable differentiation between these areas in humans in a number of studies [22–24,33].

Despite evidence demonstrating differences between MT/TO-1 and MST/TO-2 in terms of the extent of RF coverage of their constituent neurons and functional differences relating to motion processing, few studies have examined the whether this extended ipsi-lateral coverage within MST/TO-2 corresponds to functional processing of ipsi-lateral stimuli. Presumably, this is due to the expectation that when testing ipsi-lateral function it is difficult to negate the contribution made to perception by the contra-lateral visual areas. For example, a stimulus located in the visual field ipsi-lateral to left hemisphere, would be located in the contra-lateral field of the opposite (right) hemisphere. Despite this difficulty, evidence from transcranial magnetic stimulation (TMS) experiments has demonstrated that motion detection can be impaired in the ipsi-lateral hemi-field following application of TMS to both left and right hV5/MT+ [35]. Interestingly, the induced functional deficits were greater for ipsi-lateral stimuli when TMS was applied to the right hemisphere, compared to when TMS was applied to left hV5/MT + . However, a drawback of this study was that hV5/MT + was treated as a single entity and there was no consideration of the potentially different contributions of the MT/TO-1 and MST/TO-2 sub-divisions. A parsimonious explanation for above finding might simply lie in the fact that MST/TO-2 was unequally stimulated across the left and right hemispheres. As a consequence of its neurons having larger RFs which extend further into the ipsi-lateral field than those in MT/TO-1, any bias towards stimulation of MST/TO-2 could in theory be responsible for larger deficits observed for ipsi-lateral stimuli. Given that it is possible to now localise these sub-divisions of hV5/MT + independently, by utilising their respective receptive field properties, the question then arises: are there genuine functional differences between MT/TO-1 and MST/TO-2 within the ipsi-lateral visual field, and if so, are these differences consistent across hemispheres?

The existence of a right hemisphere bias in the perception of ipsi-lateral motion stimuli would have resonance with studies that point to a more prominent role for the right cerebral hemisphere in the allocation of spatial attention [36]. Patients with right or left unilateral damage to their parietal cortex tend to exhibit neglect of objects located in the visual hemi-field contra-lateral to the lesion site [37]. However, this neglect tends to be more common and severe when cortical damage occurs to the right hemisphere [38]. Of particular relevance to this study, is the fact that patients with damage to the right hemisphere also show neglect for targets placed in the hemi-field ipsi-lateral to their lesion site [39,40]. These findings have been interpreted as evidence for a right hemisphere dominance in the rapid deployment of transient attention [35], the shifting of spatial attention leftwards and rightwards [36] or reciprocal inter-hemispheric inhibition [41].

The purpose of this study was to investigate whether MT/TO-1 and MST/TO-2 exhibit genuine functional asymmetries across the left and right cerebral hemispheres in terms of their processing of ipsi-lateral motion stimuli. Using previously adopted techniques to localise and differentiate the MT/TO-1 and MST/TO-2 sub-divisions within hV5/MT+ [33,31,42], fMRI-guided TMS was delivered to these areas in both cerebral hemispheres whilst the ability to perceive direction of translational dots in both the contra- and ipsi-lateral visual fields was measured using psychophysical procedures.

2. Methods

2.1. Subjects

Nine individuals were recruited, but due to exclusion criteria (see Fig. 2) seven subjects took part in this study (five male; mean age 27.1; age range 21–46 years). All subjects had normal or corrected-to-normal vision at the time of testing and no history of psychiatric or neurological disorders. Experiments were conducted in accordance with the Declaration of Helsinki and accepted TMS safety protocols [43,44], and were approved by both the York Neuroimaging Centre Ethics Committee and the University of Bradford Ethics Committee.

2.2. MRI and analysis

Functional T2* MR images were acquired using a GE 3-Tesla Sigma Excite HDX MRI scanner at York Neuroimaging Centre, and functional paradigms were identical to those described previously [33]. Gradient-recalled echo pulse sequences were used to measure blood oxygenation level dependent (BOLD) signal as a function of time (TR = 3000 ms, TE = 29 ms, FOV = 192 cm, 128 × 128 matrix, 39 contiguous slices, 1.5 × 1.5 × 1.5 mm^3, interleaved slice order with no gap), and magnetisation was allowed to reach a steady state by discarding the first three volumes. A 16-channel phased-array half-head coil positioned at the occipital pole of the subject was used to measure MR signal focused on the visual cortex. Each subject saw a minimum of 3 repeat scans for each hemi-field totalling 75 volumes per stimulus; 300 total volumes per hemifield (see [33] for further explanation of this method). A high-resolution T1-weighted 3D anatomical data set was used for co-registration of functional and structural data. This was acquired using an 8-channel phased-array full-head coil (TR = 7.8 ms, TE = 3 ms, TI = 450 ms, FOV = 290 × 290 × 276, 256 × 256 × 176 matrix, flip angle = 20°, 1.13 × 1.13 × 1.0 mm^3). The data obtained from these functional scans were analysed using BrainVoyager QX software (Version 3.0, Brain Innovation). Pre-processing of this data included spatial smoothing (3 mm Gaussian kernel, full width at half maximum), 3D motion correction, slice scan timing correction, and high-pass (GLM-Fourier) temporal filtering (0.01 Hz). For the motion correction, translation and rotation parameters were inspected; if they exceeded 2 mm, the run was either removed from the analysis or repeated. Multiple linear regression was then applied to the data allowing contrasts to be made between moving–static conditions within each subject across multiple runs. Haemodynamic responses were corrected appropriately for neurovascular lag [45].

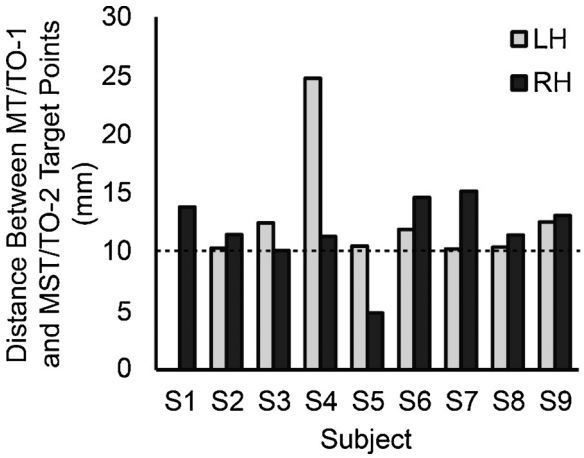

Fig. 2. Bar chart showing Euclidean distances (in millimetres) between MT/TO-1 and MST/TO-2 in the left (LH; light grey bars) and right hemisphere (RH; black bars) for each subject. The black dashed line denotes the 10 mm separation criterion. S1 and S5 were excluded from further experiments as no areas were identified in the left hemisphere of S1, and S5 possessed target points that fell short of the 10 mm criterion.

2.3. Identification and localisation of regions of interest

The two experimental regions of interest (ROIs), MT/TO-1 and MST/TO-2 were identified in each subject using functional localisers described previously [33]: hV5/MT + was identified as the entire cluster of activity to stimulation of the contra-lateral visual field; this cluster is segmented by subtracting the voxels active during ipsi-lateral field stimulation (i.e. the MST/TO-2 cluster) leaving the MT/TO-1 cluster (see Fig. 1). A control ROI (LO-1) was identified in both hemispheres using standard retinotopic mapping techniques involving rotating checkerboard wedges (polar angle) and increasingly eccentric checkerboard rings (eccentricity) [46,47]; also see [33] for a more detailed description of all functional scanning. All identified ROIs were localised for both the left and right hemisphere in each subject, and the centre-of-mass co-ordinates were used as target points for the TMS. Average Talairach co-ordinates for the centre-of-mass co-ordinates corresponding to MT/TO-1 and MST/TO-2 in both hemispheres have been published previously [33]. Any subject with ROIs possessing a Euclidean distance of less than 10 mm in NATIVE co-ordinates were excluded from the experiment as the spread of the TMS would not permit distinct stimulation of the individual sites (see [33] for an explanation). Additionally, one subject (S1) only successfully saw two

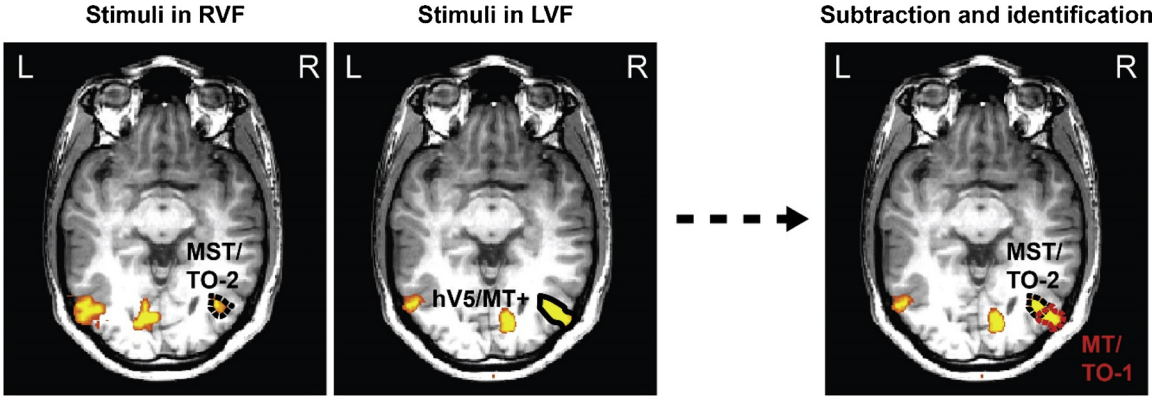

Fig. 1. Diagram showing identification of MT/TO-1 and MST/TO-2 using the left hemisphere of one representative subject (S7) as an example. The fMRI data show the BOLD signal ($p < 0.001$) generated by moving vs static functional localisers presented in both left (LVF) and right visual field (RVF) (averaged across four runs). Stimuli presented in the contra-lateral visual field (RVF) activate the entire left hV5/MT + complex (white solid line), whilst ipsi-lateral stimuli (LVF) restrict activation to the anterior portion: MST/TO-2 (white dashed line). During analysis, subtraction of the MST/TO-2 ipsi-lateral activation (white dashed line) from the whole hV5/MT + complex (white solid line) contra-lateral activation parcellates the remaining portion of hV5/MT + into MT/TO-1 (yellow dashed line).

repeats of the localiser presented to the left visual field and as such identification of left MT/TO-1 and MST/TO-2 was not possible. Subjects S2, S3, S4, S6, S7, S8, and S9 from [33] participated in this experiment (Fig. 2).

2.4. Behavioural/TMS paradigm

All stimuli were displayed on a high-resolution cathode ray tube monitor with a refresh rate of 75 Hz (Mitsubishi DiamondPro 2070SB) and were generated using Psychophysics Toolbox Version 3 [48–50] in 32-Bit MATLAB (Version 7.6.0; The MathWorks Inc., Natick, MA, 2008). Dot stimuli were restricted to a 10° circular aperture containing 300 white (RGB [145,145,145]) dots on a black background. Each dot subtended 0.2° of visual angle (dot density ~3.82/deg^2), and all dots moved at a speed of 7°/s regardless of direction. The centre of this aperture was horizontally displaced by 15° either to the left or right of the fixation point depending on the condition of the trial (Fig. 3). In order to avoid confounding effects arising from stimuli falling within the blind spot of the either eye, an eye-patch was worn over the appropriate eye (e.g. left eye for left visual field) for each condition (see Fig. 3a). This meant that each run consisted of stimuli presented in the same hemi-field. All stimuli contained translational motion in which a predetermined, individual threshold level of signal (coherent) dots moved either up or down (cf. [33]). The remainder of the dots moved randomly (noise). At stimulus onset, each dot was randomly assigned an individual 'age' (between 1–20 frames) and throughout the presentation all dots were assigned a limited lifetime of 20 frames. If the 'age' of any dot reached 20, the dot was randomly reassigned a new location (same direction) and the 'age' was reset to 0. This maintains direction information whilst preventing a continuous stream of motion, which in turn, inhibits after-images. Each presentation of the stimulus lasted 200 ms and the inter-trial interval was a minimum of 2 s (see Fig. 3b). Subjects were required to identify the coherent direction of the signal dots using a 2-alternative forced choice (2AFC) paradigm (up or down) and were instructed to record their decision using an appropriate button on the keyboard as quickly and as accurately as possible.

In the combined TMS and psychophysical experiments, the onset of the motion stimulus was synchronous with onset of a train of 5 biphasic (equal relative amplitude) repetitive TMS pulses (Fig. 2b). Results from previous experiments had demonstrated that this temporal configuration was most effective at inducing effects in hV5/MT+ [51]. These pulses were applied to the either the left side or right side of the participant's scalp using a figure-of-eight coil (50 mm diameter) connected to a Magstim Super Rapid 2 stimulator (Magstim, Wales, UK). The repetitive TMS trains were applied at a frequency of 25 Hz, at a level of 70% of the maximum output. Subjects undertook 2 blocks of the motion task for each TMS condition with 50 trials in each block. In total there were eight conditions including: no TMS/ baseline in each visual field, and MT/TO-1, MST/TO-2, and LO-1 in each hemisphere. Only one condition was tested in each session, and the order of presentation of conditions was counter-balanced across subjects. TMS conditions included the two experimental sites in both the left and right hemisphere (MT/TO-1 and MST/TO-2), and one control site in each hemisphere (LO-1). All sites were targeted independently and the position of the coil was aligned with the target point by co-registering the subject's head with their MRI scan in BrainVoyager QX using the TMS Neuronavigator add-on. The position of the coil was monitored in real-time throughout an experimental run, and any trials in which the coil moved more than 2 mm away from the target point were discarded.

2.5. Analysis

Statistical analysis was carried out using the SPSS software package (IBM). Repeated-measures analyses of variance (ANOVAs) were calculated across all conditions (baseline, MT/TO-1, MST/TO-2, and LO-1 control) for each hemi-field, within each hemisphere (condition x hemi-field). When a significant main effect was present, pairwise comparisons were applied to the data sets (Bonferroni corrected for multiple comparisons). If a significant main effect was not found, no post-hoc analyses were carried out for that interaction. The assumption of normal distribution was confirmed with Mauchly's Test of Sphericity. If this assumption was met (i.e., sphericity is nonsignificant), then the ANOVA was calculated assuming sphericity; however, if the assumption was violated, the degrees of freedom (dF) would be corrected to allow appropriate interpretation of the F value of the ANOVA. These dF corrections included the Greenhouse–Geisser correction when sphericity was less than 0.75, and Huynh–Feldt correction when sphericity exceeded 0.75. Effect size was calculated as partial eta squared (η^2), in which a value > 0.13 is taken to indicate an effect of moderate strength. Analyses were restricted within each hemisphere initially (TMS condition x hemifield) before being compared across hemispheres (left hemisphere x right hemisphere). A post-hoc analysis of 'handedness' was performed using independent samples t-tests and Cohen's *d* was used to determine the effect size.

3. Results

Application of repetitive TMS to MT/TO-1 and MST/TO-2 during translational direction discrimination appears to produce effects that are specific to hemi-fields and hemispheres (see Fig. 4). Repeated measures ANOVAs reported significant main effects of experimental TMS condition on subject performance for contra-lateral translational motion in both hemispheres: right ($F(318) = 22.26$, $p < 0.001$, $\eta^2 = 0.79$), and left ($F(318) = 15.20$, $p < 0.001$, $\eta^2 = 0.72$).

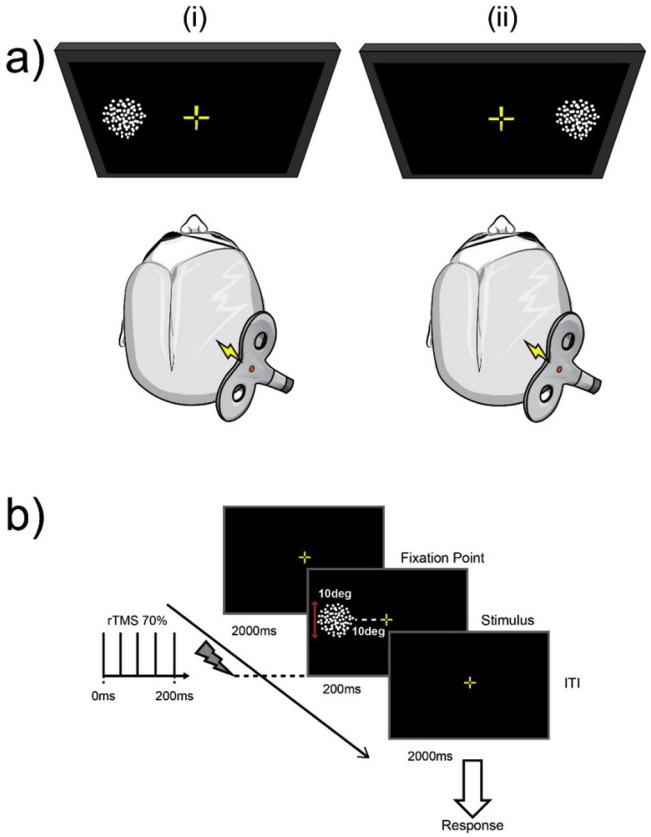

Fig. 3. Experimental TMS paradigm using the right hemisphere as an example. (a) TMS was applied to the right or left hemisphere independently and stimuli were displayed in either the left (i) or right (ii) visual field. (b). Temporal sequence of the stimulus presentation and repetitive TMS delivery, the application of TMS was concurrent with stimulus presentation. The red arrow denotes the possible direction of the moving 'signal' dots (up/down).

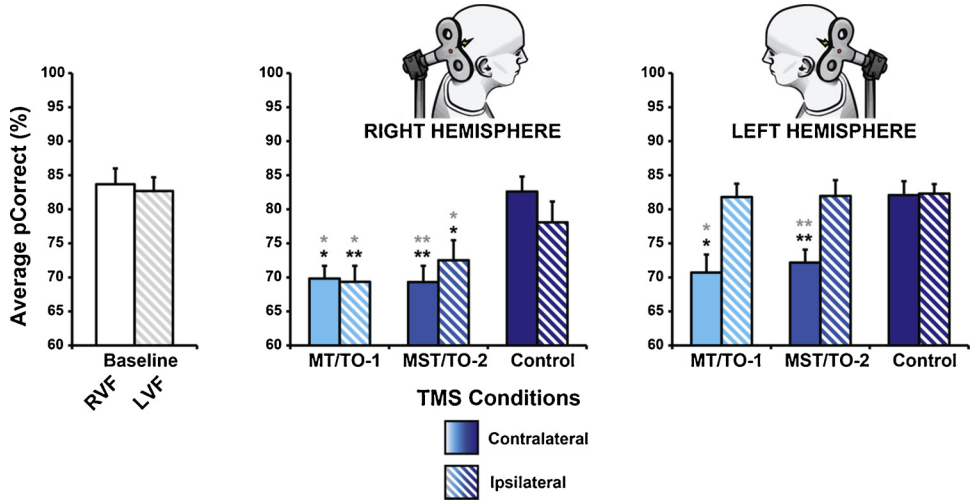

Fig. 4. Average percent correct for all conditions. Asterisks highlight conditions significantly different from baseline (black) and control (grey) at $p < 0.05$ (*) and $p < 0.01$ (**). Error bars represent S.E.M.

However, significant main effects of experimental condition were only found for ipsi-lateral translational motion in the right hemisphere ($F(318) = 21.84$, $p < 0.001$, $\eta^2 = 0.76$). No significant main effect for ipsi-lateral stimuli was found for the left hemisphere ($F(318) = 0.25$, $p = 0.861$, $\eta^2 = 0.04$).

For the right hemisphere, pairwise comparisons showed that application of TMS to both MT/TO-1 and MST/TO-2 produced significant reductions in the ability of subjects to determine the direction of motion of the dots relative to both baseline (no TMS) and control (LO-1) conditions in the contra-lateral hemi-field (MT/TO-1 versus baseline, $p = 0.012$; MST/TO-2 versus baseline, $p = 0.003$; MT/TO-1 versus control, $p = 0.024$; MST/TO-2 versus control, $p = 0.009$), and the ipsi-lateral hemi-field (MT/TO-1 versus baseline, $p = 0.005$; MST/TO-2 versus baseline, $p = 0.010$; MT/TO-1 versus control, $p = 0.040$; MST/TO-2 versus control, $p = 0.004$). No other pairwise comparisons were found to be significant ($p > 0.2$ in all cases). This indicates that within the right hemisphere, both MT/TO-1 and MST/TO-2 are essential for the perception of translational motion across the whole visual field.

In contrast, for MT/TO-1 and MST/TO-2 within the left hemisphere there was only a significant differential effect on perception when stimuli were displayed within the contra-lateral hemi-field (MT/TO-1 versus baseline, $p = 0.014$; MST/TO-2 versus baseline, $p = 0.023$; MT/TO-1 versus control, $p = 0.045$; MST/TO-2 versus control, $p < 0.001$). This suggests that MT/TO-1 and MST/TO-2 in the left hemisphere are only responsible for processing translational motion contra-laterally.

Across both hemispheres and all conditions, no significant differences between baseline performance and performance during TMS of the control site were identified. This means we can conclude that any experimental effects found are not a result of confounding variables associated with general application of TMS as this would also affect the performance associated with control site.

One final aspect of the results we examined was the hand dominance or "handedness" of the subjects. If one hemisphere appears to be functionally lateralised then it is important to rule out the effect of right- or left-hand dominance as handedness is thought to be weakly associated with atypical lateralisation of some processing such as language [52,53]. Fortunately, two of the seven subjects (S7,S8) tested here were left-handed which permitted tentative post-hoc comparisons between the behavioural data. Independent samples t-tests found no significant effect of handedness for TMS applied to the right ($t(26) = -1.60$, $p = 0.126$; $d = 0.67$) or left hemisphere ($t(8.9) = -1.83$, $p = 0.101$; $d = 0.84$), indicating that hand dominance likely does not explain the results.

4. Discussion

The results of this study reveal an enhanced role for right hV5/MT + in the processing of translational motion across the full visual field. We have demonstrated that when TMS is applied to MT/TO-1 and MST/TO-2 in the right cerebral hemisphere, deficits are induced in the perception of translational motion for stimuli located in both contra-lateral and ipsi-lateral hemi-fields. However, in marked contrast, application of TMS to the corresponding areas in the left hemisphere only disrupts the processing of translational motion for stimuli placed in the contra-lateral hemi-field. Previous studies have shown that TMS can impair ipsi-lateral motion detection when applied to hV5/MT + as a whole [30], but this is the first study to show that this effect may also hold for its constituent sub-divisions (MT/TO-1 and MST/TO-2). Importantly, the results highlight the possibility of differences in function between the human V5/MT + complex in the right and left cerebral hemispheres.

These results suggest that a degree of cortical lateralisation exists for this kind of low-level local motion analysis, similar to that which exists for other modalities such as spatial attention [2,38–41] and face perception [54], for example. Consistent with this view, other evidence in the literature also points to specific aspects of motion perception being biased towards the right hemisphere. Boulinguez and colleagues [6], for example, have reported in reaction time experiments that trajectory perception and prediction can be accessed and analysed more quickly within the right hemisphere, irrespective of handedness of the observer. This led them to conclude that the right cerebral hemisphere might not only have an increased dominance for attentional mechanisms and face perception, but also for (relatively more low-level) spatio-temporal processing tasks as well.

Further evidence for a more predominant role played by right V5/MT + in the analysis of motion signals across the full visual field is revealed by the organisation of callosal and non-callosal connections that exist between hV5/MT + across the left and right cerebral hemispheres. It has been shown that both left and right hV5/MT + are connected callosally via the splenium [55], and non-callosally through subcortical areas [56]. Importantly, researchers have correlated the microstructure of callosal connections between left and right hV5/MT + with participant's subjective experience of motion across the vertical midline, suggesting the callosal connections directly contribute to conscious motion perception [57]. Ffytche et al [56] examined visual evoked potentials (VEPs) elicited by motion stimuli from hV5/MT + across right and left cerebral hemispheres and reported that, relative to contra-lateral stimulation, the VEP exhibited a delay when

stimuli were presented ipsi-laterally. In the left hemisphere this ipsi-lateral delay was 11 ms, whereas in the right hemisphere it was significantly shorter: 3 ms. This delay is assumed to be result of the time taken for signals originating from the ipsi-lateral visual field to transfer inter-hemispherically via the corpus callosum, as it is similar to the recorded duration required for signals to cross the corpus callosum in rhesus monkeys [58]. This finding has two implications: firstly, that the cortical pathway for the processing of ipsi-lateral information is longer than that for information which originates contra-laterally, thereby indicating that the ipsi-lateral signals are transferring across hemispheres. Secondly, the right hemisphere receives the ipsi-lateral signal in approximately a quarter of the time it takes for the left hemisphere to receive the equivalent information. This implies that the right hemisphere has a considerable advantage over the left as it is granted faster access to the information arriving from the ipsi-lateral visual field [56]. This also corresponds with data from population RF mapping that shows subtly larger ipsi-lateral coverage for both MT/TO-1 and MST/TO-2 in the right hemisphere compared to the left (see Supplementary Data [24];). This advantage, coupled with the current findings where deficits in the processing of motion stimuli presented in the ipsi-lateral visual field are greater when TMS is applied to the right hemisphere compared to the left, provides complimentary evidence to support the idea of an advantage for the right hemisphere in the processing of local motion signals that extend across both ipsi- and contra-lateral visual fields. These timing biases of interhemispheric callosal signal transfer also contribute towards explaining why neuroimaging data identifies ipsi-lateral coverage in both left and right MST/TO-2 (such as the functional localisers used for this study; see also [23–25]), whilst this study reports an ipsi-lateral functional deficit restricted to the right hemisphere.

Another reason for a hemispherical dominance in the processing of both ipsi- and contra-lateral information may relate to the ability of the human brain to coherently and automatically perceive a vertically split visual scene as a single, unbroken image. Essentially, one of the obvious advantages of a visual area possessing an ipsi-lateral representation, in addition to the more typical contra-lateral representation, is that the visual field is no longer split into two distinct halves across hemispheres. This division may be offset to a certain extent by the naso-temporal overlap of RFs at the vertical meridian, but evidence from recent adaptation experiments has suggested another possibility. In a study carried out by Chen et al. [59], observers adapted to moving stimuli that were vertically misaligned across the vertical meridian. This adaptation produced a repulsive after-effect, i.e. observers demonstrated an alignment bias in the opposite direction to the one observed during adaptation. This suggests that the visual system makes sense of both halves of visual space by computing a global representation of the scene that can dynamically adapt its representation of the alignment across both hemi-fields in attempts to consistently unify the two halves. As the authors were able to demonstrate with randomly moving lines of varying orientations and rotational glass patterns, this adaptation effect must be associated with processing of both local and global features; and as all the stimuli were moving images, this makes them directly relatable to the results derived from local motion stimuli described here. The results of Chen et al. [59] clearly demonstrate the ability of the visual cortex to dynamically compare local and global information across both sides of the vertical meridian. The fact that hV5/MT + in the right hemisphere has the capability to process motion stimuli that extend across the ipsi- and contra-lateral visual fields, leads us to speculate that it may form part of a right-sided network that is central to this system which underpins this unification of perception across the two hemi-fields.

The findings of this study are broadly consistent with earlier work which has demonstrated that the application of TMS to hV5/MT + can impair the perception of visual motion in both the ipsi- and contra-lateral visual hemi-fields [35]. However, an important difference in methodological approach lies in the fact that the current study identified and targeted constituent sub-divisions of hV5/MT +; MT/TO-1 and MST/TO-2. In contrast, Thakral and Slotnik [35] localised hV5/MT + as a single entity and as a result it is difficult to be certain as to which particular sub-division was being stimulated in their study and whether this was consistent across observers. As a result of this separate targeting of MT/TO-1 and MST/TO2 we were able to demonstrate that there were negligible functional deficits induced in the perception of ipsi-laterally presented motion stimuli when TMS was delivered to the left hemisphere. However, in the right hemisphere, deficits in ipsi-lateral motion perception were found to occur when TMS was applied to both MT/TO-1 and MST/TO2. But to what extent can we be sure that our methodology has effectively dissociated the contributions of MST/TO-2 and MT/TO-1 which lie in such close proximity? When TMS is applied over a cortical region there is invariably a 'leakage' of its effects outside of the intended stimulation site into adjacent cortical areas. Our methodology was designed to minimise the influence of these 'leakage effects' and increase the likelihood of successfully dissociating these two ROIs. We have shown previously [60], as have other groups [61,62], that in order for independent effects of TMS to be consistently observed, there needs to be a separation of least 10 mm between cortical stimulation sites. This formed a basic criterion for the selection of cortical areas amenable to differentiation by TMS. All subjects in this study had centre-of-mass co-ordinates for MT/TO-1 and MST/TO-2 that were measured as being > 10 mm apart (for further information, see [33]). Adherence to this methodology has shown that it is possible to generate dissociable functional deficits in direction discrimination tasks for radial motion stimuli following application of TMS to MT/TO-1 and MST/TO-2 [33]. Lastly, and of key importance, is the fact there is no effect of TMS on performance when the control site, LO-1, is stimulated. Cortical area LO-1 was chosen as a control site because it lies in close proximity to areas MT/TO-1 and MST/TO-2, but unlike these areas, LO-1 has no known role in the processing of visual motion. The use of this control site should determine whether there are any proximity effects on performance. It allowed us to confirm that the effects of applying TMS to the target ROIs have a degree of spatial specificity and are not simply due to the general effect of applying TMS to the visual cortex. These factors provide a degree of confidence that the chosen methodology can successfully induce localised disruption to the targeted cortical areas (MT/TO-1 and MST/TO-2) that does not encroach to a significant extent (i.e. does not affect function) in adjacent cortical areas. However, limitations of repetitive TMS do remain; for instance, it is not known whether cortically disrupting an area will produce a deficit that is restricted to the function of the area itself or whether it impacts upon signal transfer across a network of connected areas [63]. In future therefore, it would be valuable to investigate connections between and within hemispheres, and examine the timing properties of signal processing within these MT/TO-1 and MST/TO-2 regions in order to determine whether right MT/TO-1 is involved in the processing of ipsi-lateral motion stimuli or whether it is simply an area involved in the proposed right hemispheric spatio-temporal network.

One novel finding lies in the contribution of right MT/TO-1 to ipsi-lateral processing. Area MT/TO-1 is identified functionally by relying on a paucity of ipsi-lateral coverage relative to MST/TO-2 (see [24,33]), so it is unexpected to find any effect of TMS to this region during presentation of ipsi-lateral stimuli. However, this finding is robust across subjects and as we have shown that our application of TMS can differentiate between functional performance across the visual field (as seen in the left hemisphere), it is likely that this result is valid. Instead, the unexpected nature of this result may be explained by the inter-hemispheric and intra-hemispheric connections between MT/TO-1 and MST/TO-2. During contra-lateral presentations, application of TMS to both MT/TO-1 and MST/TO-2 disrupts translational direction discrimination. Previous work has discussed that the contribution of both areas is likely due to a form of serial processing in which information is passed on from MT/TO-1 and subsequently subjected to more complex analysis at the level of MST/TO-2 [33]. This would mean that

degrading the signal at any stage of the serial pathway would have a detrimental effect on performance. Following this, as translational motion appears to be processed between MT/TO-1 and MST/TO-2 in a serial pathway for contra-lateral stimuli, it seems likely that a similar processing would exist for ipsi-lateral stimuli also. The signal may be transferred from the left hemisphere to right MT/TO-1 for early 'low-level' analysis before more complex analysis begins within MST/TO-2. Indeed, it would be valuable to investigate this further in future experiments.

To conclude, hV5/MT+ (incorporating MT/TO-1 and MST/TO-2) in the right cerebral hemisphere appears to have some degree of perceptual responsibility for translational motion not only within the expected contra-lateral visual field, but also the ipsi-lateral hemi-field. This is likely to arise as a result of the inter-hemispheric transfer of signals from the homologous motion processing areas in the left hemisphere. This raises questions regarding local motion processing pathways/networks and the role of interhemispheric processes in visual perception, but notably it also contributes to the growing body of literature pertaining to the idea that the right side of the brain may be lateralised for spatio-temporal perceptual decisions. Determining whether this lateralisation is restricted to processing local motion signals or whether it is involved in higher-order processes such as the unification of both hemifields into a single percept or the perception of optic flow, will be an important avenue for future research.

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